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Atomic-weight dependence of muon-pair production in 225-GeV/*c* π^--nucleus interactions

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In an experiment performed at Fermi National Accelerator Laboratory, the production of massive muon pairs in 225-GeV/*c* π^--nucleus interactions has been studied for four nuclear targets. Comparison of the relative cross sections enables the dependence on atomic weight A to be determined. If this dependence is parametrized such that the dimuon production cross section $\sigma_{\mu\mu}$ is proportional to A^α this experiment yields $\alpha = 0.98 \pm 0.04$ for $4 < m_{\mu\mu} < 8.5$ GeV/c^2, where $m_{\mu\mu}$ is the invariant mass of the muon pair.

Massive-lepton-pair production in hadronic interactions appears to be well described by the Drell-Yan mechanism of quark-antiquark annihilation.[1] That this is a relatively rare process implies that no nuclear shadowing should be present; hence one would expect the production cross section to vary as A^α, with $\alpha = 1$, where A is the atomic weight of the target. This is in contrast to the total hadronic cross section where shadowing is seen to imply $\alpha = \frac{2}{3}$. Hadron production at high transverse momentum has been observed to have A dependences with values of α in excess of unity.[2] Similarly a previous study of muon-pair production in 225-GeV/*c* pion-nucleus interactions[3] yielded $\alpha = 1.12 \pm 0.05$. Using this observed atomic-weight dependence to calculate quark structure functions, the authors of Ref. 3 concluded that their measurements were in agreement with the Drell-Yan predictions. However, a subsequent experiment[4] found $\alpha = 1.00 \pm 0.02$ but observed a cross section that was a factor of $K = 2.1 \pm 0.4$ times larger than that expected from the Drell-Yan model. Thus the present experimental status is unclear; values of $\alpha > 1$ can be interpreted as yet another appearance of the still unexplained nonlinear A dependence observed in high-P_T particle production, while a linear A dependence coupled with a normalization (K factor) of approximately 2 is supported by recent QCD calculations.[5] As part of an experiment designed to probe many of the details of massive-lepton-pair production, we have carried out a measurement of the A dependence of dimuon production in high-energy pion-nucleus interactions.

The experiment was performed in the high-intensity area of the proton laboratory at Fermilab. Typical beam momenta and intensities during data taking were as follows: a primary 400-GeV/*c* proton beam of $(2-3) \times 10^{12}$ particles per pulse produced a flux of $(5-7) \times 10^8$ 225-GeV/*c* negative pions.[6] The spread in momentum of the pion beam was ±5%, which resulted in a rms spot radius of 0.3 in. The secondary beam intensities were measured with calibrated ion chambers.[6] Four scintillation-counter telescopes viewing the target at 90° monitored the interactions in the target. The intense pion beam was of course accompanied by a muon halo generated by decays of pions in the 740-ft-long beam line. This halo was reduced to less than 1% of the pion beam with a set of iron toroidal spoiler magnets interspersed among the beam elements.

The apparatus is shown in Fig. 1. Dimensions and information on the four nuclear targets used are given in Table I. Each target, $\frac{1}{2}$ in. in diameter, intercepted 60% of the pion beam. Immediately downstream of the targets was a 48-in.-thick collimator wall which served as a hadron absorber, followed by two toroidal iron magnets, each 55 in. thick and of

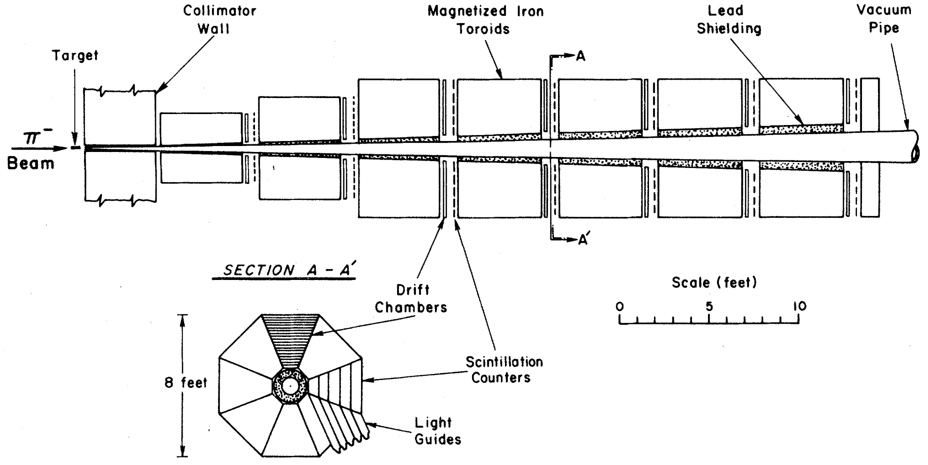

FIG. 1. Plan view of the apparatus. An end view (as seen by the beam) is shown in section *A*-*A*′.

radii 24 and 35 in., respectively. There followed five octagonally shaped magnets (shown in end view in Fig. 1) each of thickness 56 in. in the beam direction and of minor radius 47 in. The field strength of each of the magnets was measured by integrating the voltage induced in small ($\simeq 4$ in. × 8 in.) pickup coils when the magnet current was run through a hysteresis cycle. Measurements from many different coils allowed us to determine the magnetic field as a function of longitudinal position z and radius r. Internal consistency of several sets of measurements as well as good agreement with calculations lead us to estimate that we know the magnetic-field strength to $\pm 2\%$.

A conical vacuum pipe of half-angle 20 mrad permitted the noninteracting beam to pass through the center of the apparatus. Scintillation counters and drift chambers were placed downstream of each of the seven iron magnets. The inside edges of these detectors were positioned on a line from the target at an angle of 30 mrad with respect to the beam line. The conical space between the 20- and 30-mrad lines was packed with lead inside each magnet as indicated in Fig. 1.

The particle detectors at each of the seven gaps were subdivided into octants to match the octagonal symmetry of the magnets. Each subdivision (gap and octant) contained two drift chambers; one with wires perpendicular to the central radius vector in each octant and one with wires inclined at 100 mrad to this direction in order to provide narrow-angle stereo.[7] There were $7 \times 8 \times 2 = 112$ drift chambers in total. Each chamber contained two planes of sense wires displaced by $\frac{1}{2}$ wire spacing in order to resolve the left-right ambiguity. There were approximately 3500 sense wires in the array. Downstream of each set of chambers was a scintillation-counter hodoscope of matching geometry. The counters were 4 in. wide in the first two gaps and approximately 8 in. wide in gaps 3–7, with a total of 272 counters.

Fast coincidences between the scintillation counters were used to provide a preliminary trigger.[8] Counter elements in gap 1 were correlated with those in gap 2 using coincidence matrices. There was one matrix for each of the octants. Muons from the target were preferentially selected over halo muons by allowing only those matrix elements which were compatible with trajectories originating in the target. A similar set of matrices associated hodoscope planes 2 and 3 and a further set required a hit in plane 4. Thus a

TABLE I. Properties of the targets used.

Target	Length (in.)	Atomic weight	Z/A	Density (g/cm^3)	Absorption length (Ref. 10) (in.)
Beryllium	7.0	9.01	0.444	1.85	22.8
Copper	3.0	63.54	0.456	8.90	7.4
Tin	4.5	118.69	0.421	7.27	10.7
Tungsten	2.1	183.85	0.402	18.1	4.8

single muon trigger required hits in planes 1, 2, 3, and 4, pointing at the target in an octant. The pretrigger was satisfied if at least two of the eight octants contained such a muon candidate.

A further level of trigger logic required the counter hits in each of the seven planes to form a smooth trajectory coming from the target. This was done by comparing the pattern of hits with a previously stored array of acceptable trajectories. These trajectories, which were generated by a Monte Carlo simulation of the apparatus, also contained information on the most likely momentum, angle, and charge of particles generating such a pattern, thus allowing further suppression of halo muons. It was, in addition, possible to require that the muons triggering the apparatus were of opposite charge. Full details of the trigger are contained in Ref. 8.

Events satisfying these trigger requirements were written on magnetic tape. Additional criteria were developed in the off-line computer analysis of the data in order to verify that the dimuons were indeed produced in the target. For example the two particle trajectories, reconstructed from the drift-chamber information, were required to have a closest distance of approach of less than 4.5 in.; the z coordinate of the reconstructed vertex was required to fall within ± 25 in. of the target center; at the target center each track was required to be no more than 4 in. from the beam line; and the angle of the tracks had to be at least 25 mrad for positive particles (defocused by the magnetic field) or 40 mrad for negative particles (focused). Many data runs were made with none of the nuclear targets installed in order to measure a "target-out" effect. The appropriate correction (never more than 3%) was applied to the data sample for each target.

Kinematic variables such as invariant mass were calculated for all events satisfying these criteria. Events observed were in the mass range 2 to 12 GeV/c^2. The acceptance of the apparatus, extremely small for low masses, rose steeply to 5% at 6 GeV/c^2 and then slowly to 15% at 12 GeV/c^2. In order to eliminate contributions from resonances, the analysis has been restricted to dimuon masses in the interval 4 to 8.5 GeV/c^2.

The numbers of events observed for each target, together with the integrated pion flux, are shown in Table II. We calculated the cross sections for muon-pair production from each of the targets using the relation

$$\sigma_{\mu\mu}=\frac{N_{\mu\mu}A}{N_\pi N_0\rho\lambda(1-e^{-L/\lambda})},$$

where $N_{\mu\mu}$ is the observed number of dimuons, N_π is the number of incident pions, N_0 is Avogadro's number, A is the atomic weight of a target of density ρ and length L, and λ is the absorption length of the target. The acceptance of the apparatus was the same for all targets and thus cancels out in a cross-section-ratio calculation. The cross sections are displayed as a function of atomic weight in Fig. 2, where the result of the fit

$$\alpha=0.98\pm 0.04$$

is indicated. We have investigated the effect on α due to the different proton and neutron contents of each target. In the quark-antiquark-annihilation model one expects different cross sections for dimuon production in π^-p and π^-n interactions. The average cross section per nucleon for the four different targets has been calculated over the kinematical acceptance of our apparatus. It is found that if the cross section is parametrized as $\sigma_{\mu\mu}=\sigma_0(Z/A)\times A^{\alpha'}$ where Z is the atomic number, then α' differs from α by less than 1% (0.986 ± 0.04 compared with 0.979 ± 0.04). This insensitivity to neutron-proton differences can be ascribed to the similarity of the Z/A ratios for the targets used in this experiment (see Table I). We have also subdivided the data into two regions of transverse momentum, $P_T<1.5$ GeV/c and $P_T>1.5$ GeV/c, and have compared the A dependence found in each region. We find $\alpha=1.01\pm 0.05$ for the low-P_T region and $\alpha=0.94\pm 0.06$ for the higher-P_T region.

We have investigated the sensitivity of this result to variations in the definition criteria for accepted events. We have, in addition, searched for systematic differences between the events coming from each target. Various kinematical quantities were compared

TABLE II. Experimental results showing the integrated beam intensities and the numbers of dimuons produced for each target.

Target	Integrated π^- flux (N_π)	Total number of dimuons ($N_{\mu\mu}$)	$N_{\mu\mu}$ with $P_T<1.5$ GeV/c	$N_{\mu\mu}$ with $P_T>1.5$ GeV/c
Beryllium	3.9×10^{12}	159	83	76
Copper	5.7×10^{11}	36	22	14
Tin	5.5×10^{11}	54	36	18
Tungsten	9.7×10^{11}	95	54	41
Target out	8.0×10^{11}	3	0	3

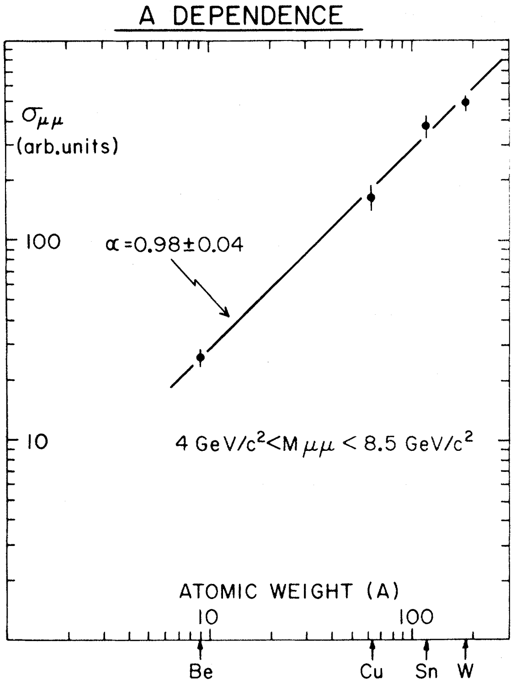

FIG. 2. Muon-pair cross sections as a function of atomic weight.

and found consistent, within statistics, among themselves and with the behavior predicted by Monte Carlo calculations. These studies suggest a systematic uncertainty of ±0.04 in the value of α.

In conclusion, we find that muon-pair production in π^--nucleus interactions is consistent with a linear dependence on the atomic weight of the target nucleus. In addition, despite limited statistics, there is no evidence that this behavior has any dependence on the transverse momentum of the muon pair. Similar results have recently been obtained by the NA 10 collaboration at CERN.[9]

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